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Models for Dust and Molecular Emission of High-Mass Protostars

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Abstract. We present the results of a detailed modeling aimed to reproduce the spectral energy distribution (SED) of dust and molecular line emission of massive protostars under the hypothesis that they form via an accretion process. We model the emission originated in the infalling envelopes at scales smaller than 0.1 pc from the central protostar. To do that, we compared our model results with observational data covering a wide range of wavelengths, paying special attention to the high angular resolution mid-infrared data obtained with the Gemini Observatory and the ammonia line emission observed with the VLA at centimeter wavelengths. We have explored two kind of model envelopes. In the first kind of models, spherical symmetry is assumed and the SED as well as the ammonia emission of the infalling envelope are calculated. In this way, the temperature, density, velocity, velocity dispersion, and ammonia abundance variations along the core can be obtained. The second approach takes into account deviations from the spherical symmetry, and parameters such as the rotation, degree of elongation of the core, or inclination of the system can be constrained through the SED fitting. Using these two approaches we have been able to model the formation of massive stars with a degree of detail similar to that reached for the low mass stars.

1. Introduction

In this paper we summarize the results of some of our attempts to model the spectral energy distribution (SED) of dust as well as the molecular line emission of hot molecular cores (HMCs). Hot molecular cores are dense ($10^6 - 10^8$ cm^{-3}), hot (100-300 K), and small ($< 5''$) condensations located in the vicinity of ultracompact HII (UCHII) regions. They are characterized by strong continuum millimeter dust emission, molecular lines of high excitation levels, and are frequently associated with water masers. Despite these physical conditions indicative of a powerful central source, HMCs are not associated with significant centimeter free-free emission. The study of this kind of sources has gained interest in the last years because it has been shown that they may be tracing a phase prior to the formation of an UCHII region, and therefore they may represent one of the earliest observable phases in the formation of a massive star.

The main hypothesis of our models is that massive stars are formed via an accretion process. Under this hypothesis a HMC is simulated as an envelope infalling onto a massive protostar, where the main source of energy is coming from the luminosity of the star and the accretion shock. For the geometry of the envelope two approaches are adopted. In a first approximation, spherical envelopes

are assumed (Osorio, Lizano & D'Alessio 1999) with a density distribution resulting from the collapse of the singular logatropic sphere (SLS, McLaughlin & Pudritz 1997). For a given stellar mass and mass accretion rate the SLS collapse solution is able to determine the complete physical structure of the envelope. In the second approach, non-spherical envelopes are adopted. These envelopes are elongated not only in the inner region due to rotation but also at large radii due to intrinsic flattening of the core (De Buizer, Osorio & Calvet 2005). In addition to the dust emission, the molecular line emission is obtained for the physical parameters of the collapsing SLS derived from the fit to the observed SED (Osorio et al. 2007). The only free parameter in the line fitting is the gas-phase molecular abundance.

It is important to emphasize that to properly model the properties of HMCs high angular resolution observational data are required in order to distinguish the emission coming from the HMC from that of nearby UCHIIs. For this reason, in our modeling we use preferentially high angular resolution data. In the following sections we summarize briefly these models.

2. Spherical Envelopes

Osorio et al. (1999) modeled the SED of several prototypical HMCs using mostly submillimeter and millimeter high angular resolution ($< 5''$) data. For these sources only upper limits of the flux density were available at near- and mid-infrared wavelengths, so spatial intensity profiles at millimeter wavelengths were used to further constrain the parameters of the model. The density structure of the core was determined by the SLS collapse solution, characterized by a stellar mass and a mass accretion rate, obtained from the fit to the observed SED. These two parameters also determine the source of heating ($L_* + L_{\rm acc}$) and allow to derive the temperature gradient inside the core.

In this way, Osorio et al. (1999) show that the dust continuum emission of the HMCs can be explained as arising in massive envelopes collapsing onto early spectral type (B) stars with high mass accretion rates (10^{-4}-10^{-3} $M_\odot$ yr^{-1}). In these objects the accretion luminosity is the main source of heating. This work shows that massive stars up to a mass of 20 $M_\odot$ can be formed via accretion since the radiation pressure does not halt the collapse.

3. Flattened Envelopes

De Buizer et al. (2005) imaged the near- and mid-infrared emission associated with high-mass protostellar objects using the Gemini telescope with high angular resolution ($< 1''$). Unfortunately, the SED of these sources was not well sampled in the millimeter wavelength range, which is very sensitive to the density and luminosity of the sources, and high angular resolution millimeter data was available for only one of the sources. Nevertheless, since the mid-infrared range is very sensitive to the geometry of the source (see Fig. 1) it was possible to study departures from spherical symmetry using more realistic models. Elongated envelopes with flattening due to rotation at small radii and with intrinsic flattening at large radii were adopted. This kind of envelope is similar to the Terebey et al. (1984) solution (TSC envelope) in the inner region but it has been

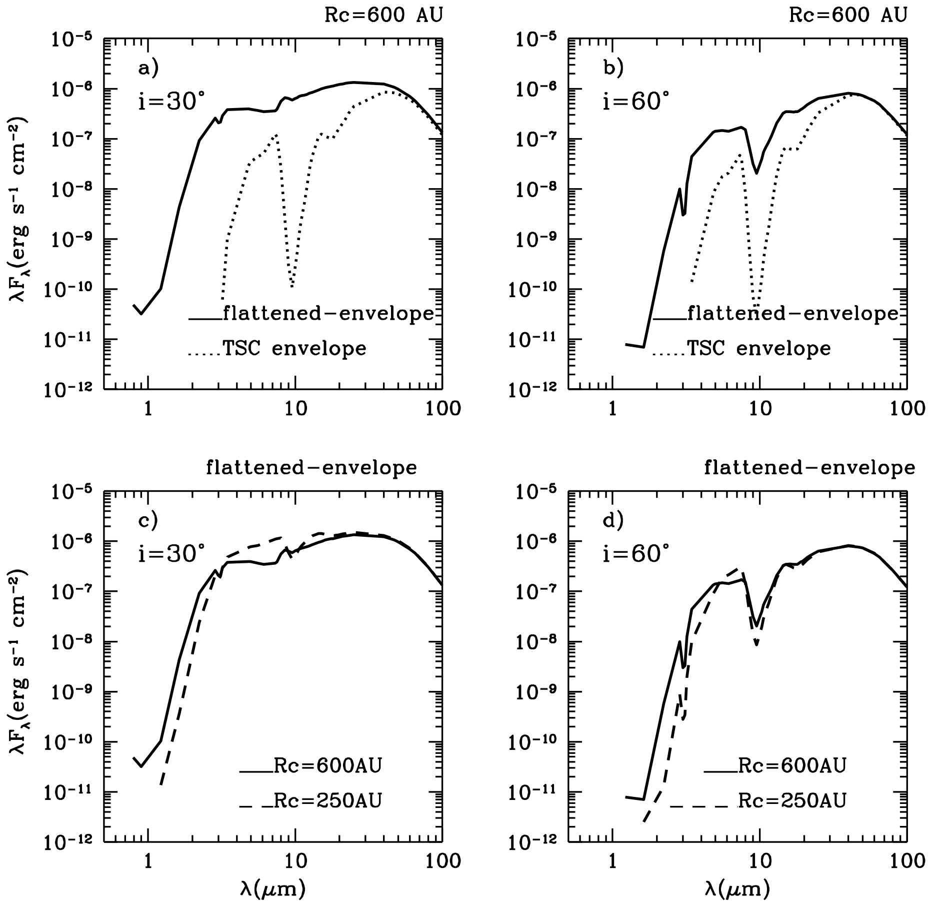

Figure 1. (a) Model SEDs for an intrinsically flattened envelope (solid line) and a TSC envelope (dotted line) with the same value of the centrifugal radius ($R_c = 600$ AU) and inclination angle ($i = 30°$). (b) Same as (a), but for a higher value of the inclination angle ($i = 60°$). (c) Model SEDs for two intrinsically flattened envelopes, with the same value of the inclination angle ($i = 30°$) and two different values of the centrifugal radius: $R_c = 250$ AU (dashed line) and $R_c = 600$ AU (solid line). (d) Same as (c), but for $i = 60°$. The stellar luminosity ($L_* = 25000\ L_\odot$), the mass of the envelope ($M_{env} = 9\ M_\odot$), and the assumed distance (1 kpc) are the same in all models (adapted from De Buizer et al. 2005).

modified at larger radii (Hartmann et al. 2006) to simulate more realistically the shape of the star-forming core. In that work, parameters such as the inclination of the system, the centrifugal radius (where the rotation becomes important), the luminosity, and the mass accretion rate are derived.

As an example, in Figure 2 we show the observed and model SEDs for the prototypical HMC near the UCHII region G29.96-0.02 (G29 HMC). This is one of few hot cores with both mid-infrared and millimeter emission data. The SED of G29 HMC can be explained by an early type (B) star with a very high mass

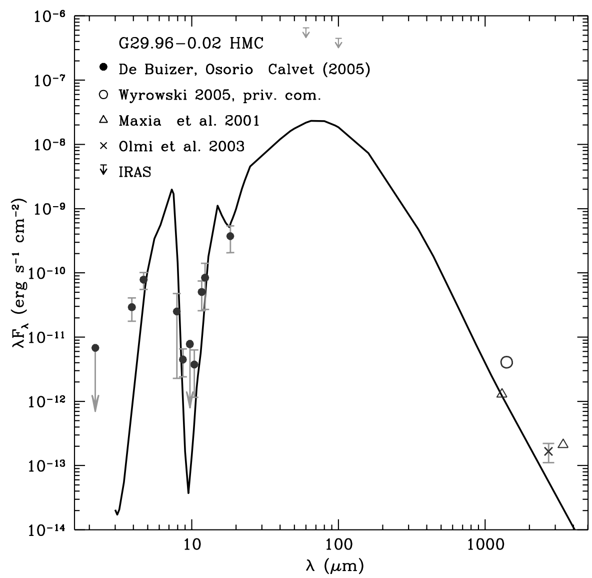

Figure 2. Model SED for the source G29.96-0.02 HMC. The different symbols represent the observed values of the flux density. Solid line represents the best fit model, obtained with $i = 12°$, $R_c = 570$ AU, $L_* = 1.8 \times 10^4\ L_\odot$, and $\rho_{1\,\mathrm{AU}} = 3 \times 10^{-11}$ g cm^{-3}. The adopted distance is 8.4 kpc (adapted from De Buizer et al. 2005).

accretion rate ($\sim 10^{-2}\ M_\odot$ yr^{-1}), a centrifugal radius of the order of 600 AU and an inclination angle near to the pole-on position. It is worth noting that the centrifugal radius (i.e., the radius where the formation of disks is expected to occur) found for G29 HMC is in good agreement with the radius obtained from high-angular resolution observations of the disk in Ceph A HW2, one of best examples of a disk around a high-mass protostar (Patel et al. 2005, Torrelles et al. 2007).

A grid of SEDs for high-mass protostars, assuming rotationally flattened envelopes with disks and outflows, has been presented by Robitaille et al. (2007). However, the observational dataset of HMCs is still scarce and their SEDs from near-infrared to millimeter wavelengths are not well covered, making difficult to constrain for these objects the large number of free parameters of these models.

4. Modeling of the Molecular Emission: Ammonia Lines

The SED alone cannot provide a full description of the physical properties of the HMCs. Complementary information can be obtained from the modeling of the molecular emission that is sensitive to velocity motions such as infall, turbulence, or rotation. Osorio et al. (2007) present a modeling procedure aimed to reproduce simultaneously both the SED and the ammonia line emission of HMCs. The only free parameter in this molecular modeling is the ammonia gas-phase abundance.

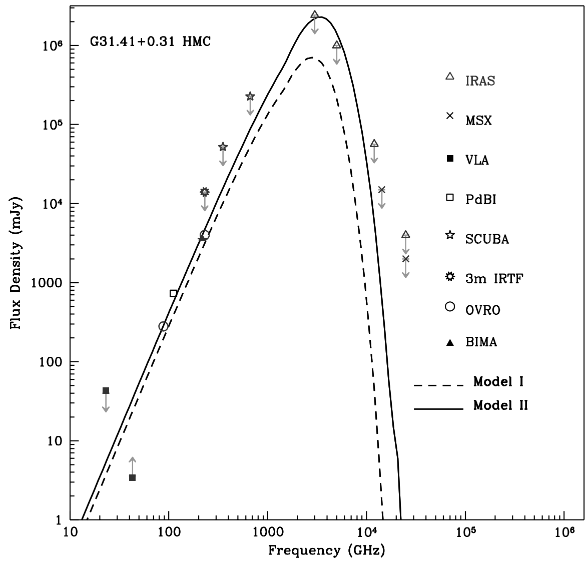

Figure 3. Observed flux densities of G31 HMC and predicted SED for Model I (dashed line) and Model II (solid line). (adapted from Osorio et al. 2007).

This modeling procedure has been applied to the hot core near the UCHII region G31.41+0.31 (G31 HMC). G31 HMC has a quite wide observational set of dust emission data, and has been observed in several ammonia inversion transitions. In particular, the NH_3(4,4) transition has been observed with the VLA with subarsecond angular resolution (Cesaroni et al. 1998). These observations reveal variations of the ammonia emission as a function of distance to the center of the core.

In order to calculate the molecular emission, the density, temperature, velocity, and velocity dispersion inside the core are required. Osorio et al. (2007) fitted the SED of G31 HMC adopting the physical structure of the SLS collapse. Due to the incompleteness of the observational data, two models were found to be consistent with the observations (see Fig. 3). Model I has a stellar mass of 12 $M_\odot$ and a mass accretion rate of 1.6×10^{-3} $M_\odot$ yr^{-1} and Model II has a stellar mass of 25 $M_\odot$ and a mass accretion rate of 2.7×10^{-3} $M_\odot$ yr^{-1}, which results in a more luminous envelope (2.3×10^5 $L_\odot$) than Model I (5.0×10^4 $L_\odot$). Therefore Model II has a higher temperature than Model I at any radius (see Figure 4).

For a given physical structure of the core the gas-phase ammonia abundance is the only free parameter to calculate the ammonia emission. As a first approach, a constant gas-phase ammonia abundance inside the core was assumed, and a grid of cases was run for a wide range of values of the ammonia abundance. However, none of the two models could reproduce the VLA ammonia (4.4) spectra obtained by Cesaroni et al. (1998).

As a second approach, Osorio et al. (2007) considered that the total abundance of ammonia molecules as a function of radius remains constant inside

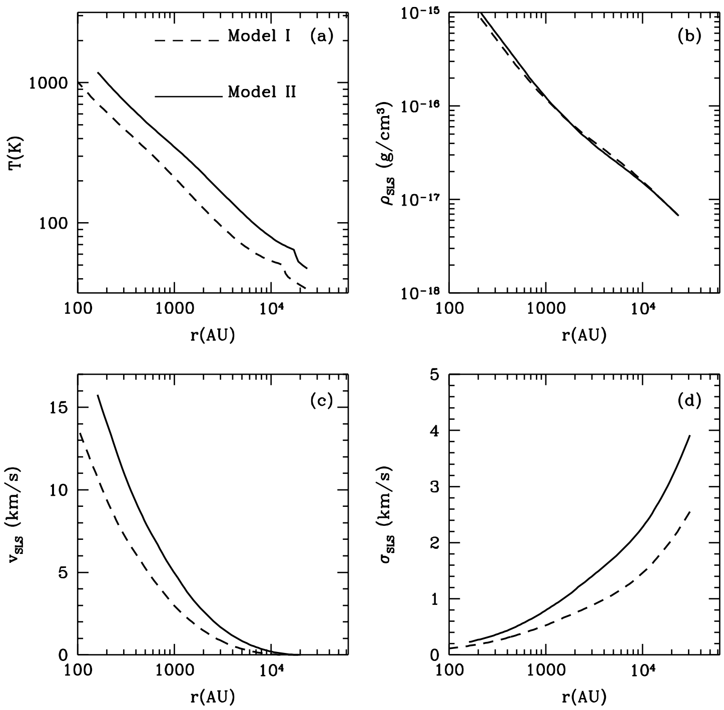

Figure 4. Physical structure of the G31 HMC for Model I (dashed line) and Model II (solid line line). (a) Dust temperature as a function of radius; (b) Gas density as a function of radius; (c) Infall velocity as a function of radius; (d) Turbulent velocity dispersion as a function of radius. (adapted from Osorio et al. 2007).

the envelope (no chemical effects) but the ratio of solid to gas-phase molecules changes as a function of density and temperature inside the core, being described by an equation of thermal balance between sublimation and condensation (Sandford & Allamandola 1993). This appears to be a more realistic description since it is expected that ammonia molecules are trapped in water ice mantles of dust grains in the outer (colder) regions of the core being released to the gas phase in the inner (hotter) regions where water molecules are sublimated. Therefore, a rapid enhancement of the gas-phase ammonia abundance is expected at the radii where temperatures above ~ 100 K (the sublimation temperature of water, for the typical densities of HMCs) are reached. The maximum and minimum gas-phase ammonia abundances are, thus, the free parameters to be adjusted in this line fitting.

After running a grid of cases it was found that Model I was unable to fit the VLA ammonia (4,4) data. However, a reasonably fit was found for Model II. This fit reproduces the observed intensity of the main and satellite lines as a function of the projected distance to the center, as well as the observed line widths (see Fig. 5, left). In this best fit, the gas-phase ammonia abundance has a minimum value of 2×10^{-8}, typical of the average values reported in the

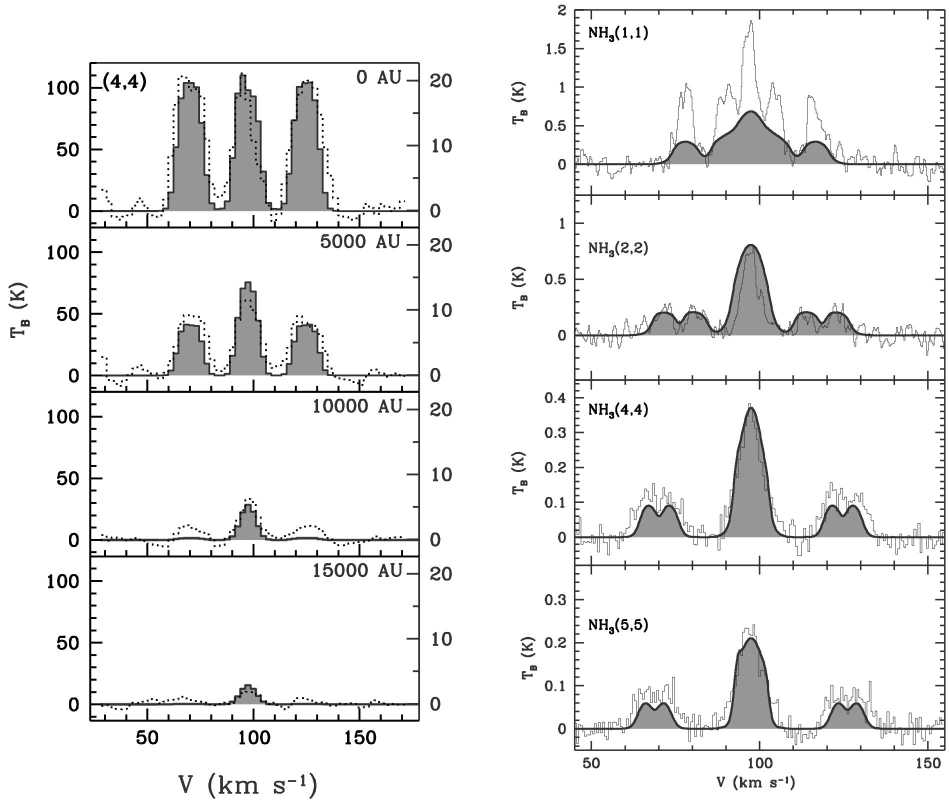

Figure 5. *(Left)* Synthetic spectra of the $NH_3(4,4)$ transition (solid line with gray area) for Model II as a function of the projected distance to center of the G31 HMC core. The spectra have been obtained assuming a variable gas-phase NH_3 abundance along the envelope with a minimum value of 2×10^{-8} and a maximum value of 3×10^{-6}. The observed spectra (adapted from Fig. 9c of Cesaroni et al. 1998) are plotted in each panel as dotted lines. The angular resolution is $0\farcs63$. *(Right)* Synthetic spectra (solid line with gray area) of the $NH_3(1,1)$, $NH_3(2,2)$, $NH_3(4,4)$, and $NH_3(5,5)$ transitions towards the center of the HMC, for an angular resolution of $40''$. The model parameters and ammonia abundances are the same as in the left panels. The spectra observed with the 100 m telescope (Cesaroni et al. 1992) are also shown (thin line). To facilitate comparison, the observed (2,2) and (5,5) spectra have been scaled down 30% (the uncertainty in the absolute calibration of the observed spectra). (adapted from Osorio et al. 2007).

literature for cold cores, and a maximum value of 3×10^{-6}, typical of the average values reported for massive cores.

The set of physical parameters derived from the fit to the SED and the ammonia abundances derived from the fitting of the VLA $NH_3(4,4)$ spectra can also reproduce satisfactorily other ammonia transitions. Figure 5 (right) shows the spectra of the NH_3(1,1), NH_3(2,2), NH_3(4,4), and NH_3(5,5) transitions observed with the 100 m telescope (Cesaroni et al. 1992). To facilitate comparison, the observed (2,2) and (5,5) spectra have been scaled down 30% (the uncertainty in the absolute calibration of the observed spectra). As can be seen in the figure,

the model reproduces quite well the observed spectra, except for the $NH_3(1,1)$ transition, were there is likely a contribution of cold molecular gas from outside the core, which is not considered in our modeling.

5. Conclusions

- A spherically symmetric model of the collapse of a SLS can explain the observed SED and the intensity spatial profiles of the continuum dust emission of HMCs, implying that these objects are dominated by accretion.
- In order to fit the data a young, early type central star with a high mass accretion rate is required. These results strengthen the hypothesis that HMCs are one of the earliest observable phases of massive star formation.
- Inclusion of rotation and the natural elongation of the cloud allows to fit the high angular resolution mid-IR data providing a determination of additional physical parameters such as the inclination angle or the centrifugal radius. Values of a few hundred AUs are found for this radius, similar to those obtained in high angular resolution observations of disks around massive protostars.
- The ammonia emission and its variation across the core can be reproduced in great detail provided the variation of the gas-phase ammonia abundance due to sublimation of the ammonia molecules from ice grain mantles because of the temperature gradient inside the core is taken into account.
- This kind of modeling would be required to explain the details of the observational data that are expected to come from the new generation of high angular facilities (EVLA, ALMA,...).

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